Fall 2022

MEMS 411: Dynamic Seal

Devin Fredericks

Abdul Majeed Lalani
Washington University in St. Louis

Matthew Schmidt
Washington University in St. Louis

Edward Tinnemeyer
Washington University in St. Louis

Washington University in St. Louis
James McKelvey School of Engineering

Mechanical Engineering Design Project
MEMS 411, Fall 2022

Dynamic Seal

The purpose of this design project is to design a dynamic seal to be used on AirCapture's carbon capture machine. The task is to create an air-tight seal between the top and bottom halves of AirCapture's carbon capture machine. The seal needs to be capable of periodically rotating and must not leak while in operation. We approached the project by examining existing dynamic seal designs and understanding the existing design by AirCapture. This is because the seal design must be compatible with AirCapture's machine. Some of the needs of the customer were that the seal must require little to no maintenance and must avoid damage to the current carbon capture machine. A smaller-scale rig was built to test potential design ideas for the seal in a controlled manner. This rig consisted of a trough to test pressure difference and a motor to provide a similar function as AirCapture's rotating machine. The rig was built in place of a mock-up prototype since we prioritized constructing a testable seal with a rotating bottom half. To measure the seal's capability and effectiveness prototype performance goals were created. By simulating the rotation of the carbon capture machine, we can then effectively test seal designs under realistic conditions and suggest the best-performing design to AirCapture. This report will go over the design process of the dynamic seal from researching similar existing devices to creating a final prototype design along with its performance goals to be shared with AirCapture. Thus, giving the customer a new design for their dynamic seal component.

TINNEMEYER, Edward
LALANI, Abdul Majeed
FREDERICKS, Devin
SCHMIDT, Matt

Contents

List of Figures

List of Tables

1 Introduction

Carbon capture machines have become increasingly important in recent years due to the widespread insight of climate change and global warming. By collecting carbon from the air we can reuse the by-product to then further minimize carbon emissions made by giant corporations. When working on carbon capture machines it's important to prevent leakages to not further damage the surrounding environment.

For this mechanical engineering design project, we will be designing a dynamic seal for AirCapture's Direct Air Capture (DAC). This carbon capture machine will need to rotate periodically. In addition, the seal must be active when the DAC is in operation. The design of the dynamic seal must require little to no maintenance and must have a long operating life span. The DAC will need to be protected against coastal environments, as this is one of the more harsh environments that it will operate in.

2 Problem Understanding

2.1 Existing Devices

A dynamic seal is a seals that are used to produce a barrier between a moving surface and a stationary surface. There are about 7 different kinds of dynamics seals which include: Packing Seal, Mechanical Seal, Dry Gas Seal, Labyrinth Seal, Oil Seal, Power Seal, and Spiral Seal. A dynamic seal will be used to focus where the air is flowing into the machine.

2.1.1 Existing Device #1: CEFIL'AIR Inflatable Seal

Figure 1: Inflatable Seal (Source: CEFIL'AIR)

Link: https://technetics.com/products/cefilair-inflatable-seals/#specifications
Description: The CEFIL'AIR inflatable seals are inflated and retracted by a pneumatic process and made of advanced elastomers. This seal is offered in a wide variety of materials with highly

resistant mechanical and physical properties to ensure a long lifetime. This seal is applicable for moving, handling, and clamping large, fragile, or complex objects.

2.1.2 Existing Device #2: Buna-N Rotary Shaft Seals

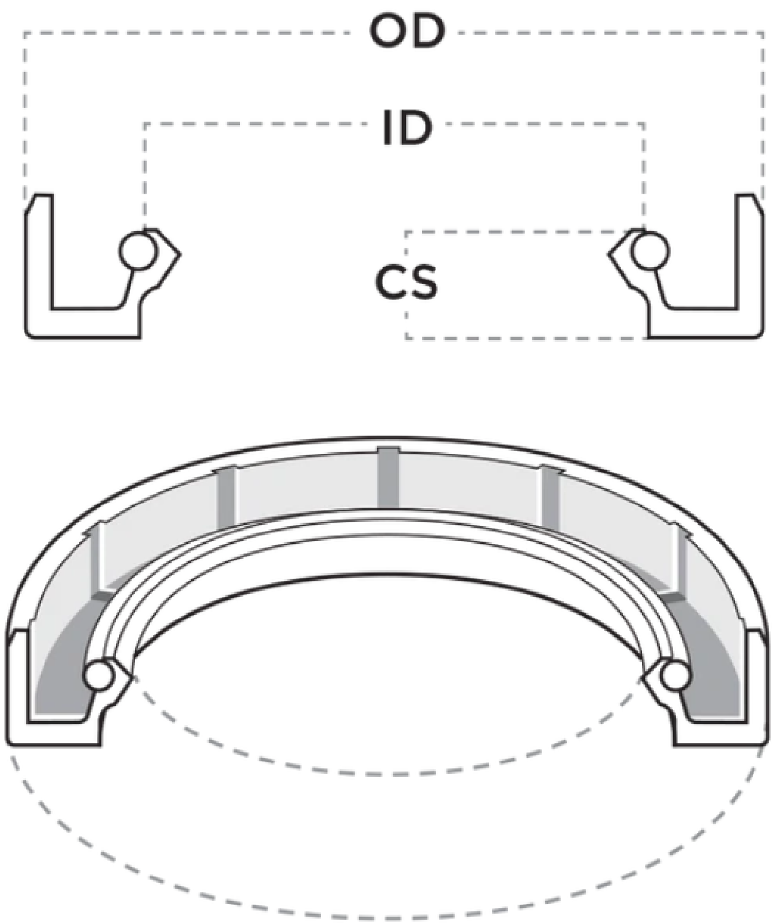


Figure 2: Rotary Seal (Source: Buna-N)

Link: https://usasealing.com/collections/standard-rotary-shaft-seals/products/buna-n-rotary-variant=36895158342

The Buna-N rotary seal, aka oil seal, is most often used on rotating shafts. These seals are made of rubber and supported by a metal spring to provide an additional sealing force. These specific seals can withstand a pressure of 10 PSI. For this seal to work, a shaft goes through the bottom of the seal stretching the inner ring to create a sealing force while allowing for the shaft to rotate.

2.1.3 Existing Device #3: CF Non-Contact Labyrinth Seal

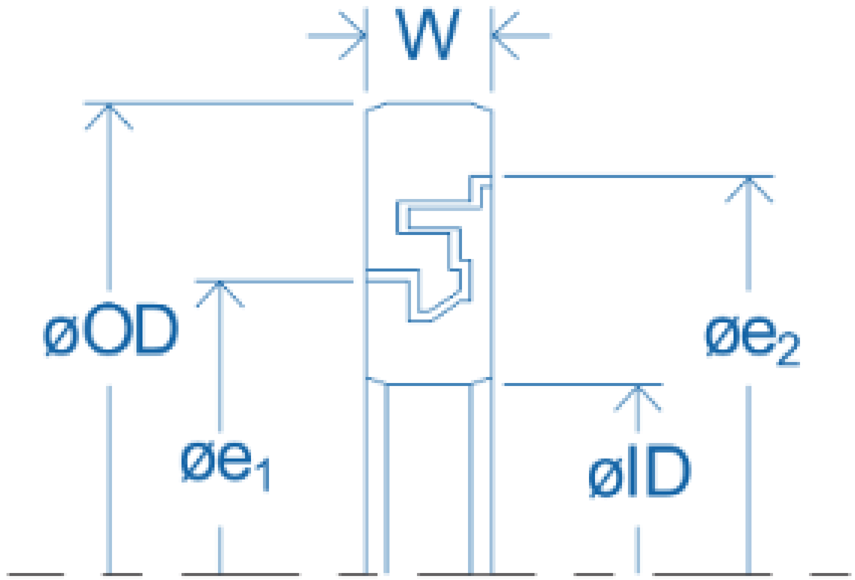


Figure 3: Labyrinth Seal (Source: GMN Bearing USA)

Link: https://www.gmnbt.com/labyrinth-seals/cf-seals/

The CF Non-Contact Labyrinth seal is a that is able to provide 100% sealing against liquids while rotating or still. Since this seal is a non-contact seal, there is no rotating friction, no increase in temperature, and a theoretically limitless lifespan. Labyrinth seals work by creating areas of turbulent flow to exclude contaminants.

2.2 Patents

2.2.1 Dynamic seal using vulcanization of fluorocarbon elastomers (US8485533B2)

This patent is for a dynamic seal placed in between rotating components. The model describes a ring that will be fixed to one of the components with a radial seal extending from the ring. The radial seal will be made of a rubber composition (vulcanized fluorocarbon elastomer) that will slide against the component without the attached ring. In addition, changes can be made to the seal to decrease or increase seal effectiveness with a spiral groove or a circumferential spring.

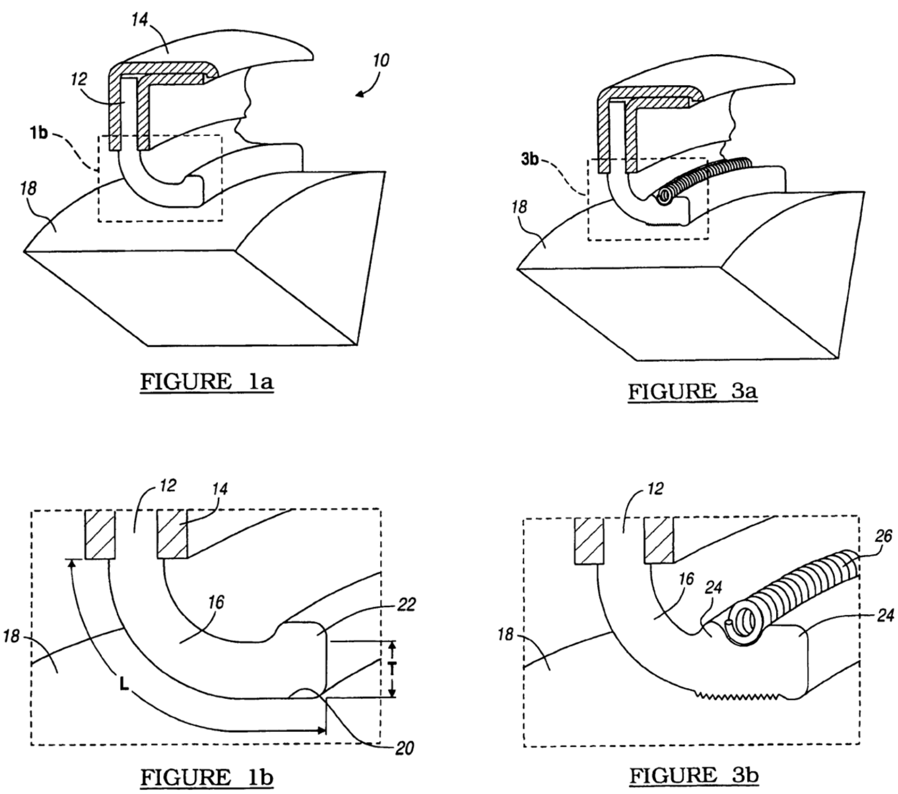


Figure 4: Patent Images for Dynamic seal using vulcanization of fluorocarbon elastomers

2.2.2 Non-contacting dynamic seal (US20200271006A1)

This patent is used for gas turbines, however, the techniques and concepts used for this patent can be applied to a carbon capture machine. This complex patent describes a dynamic seal with no "contact" between the rotating components. This is done with a pocket of air in between the members. As the seal is rotated, based on radial speed and temperature, the seal will either expand or contract. When the seal expands a seal is produced due to the geometry of the rotating shoe. A wave spring is used to dampen the vibrations produced at high speeds.

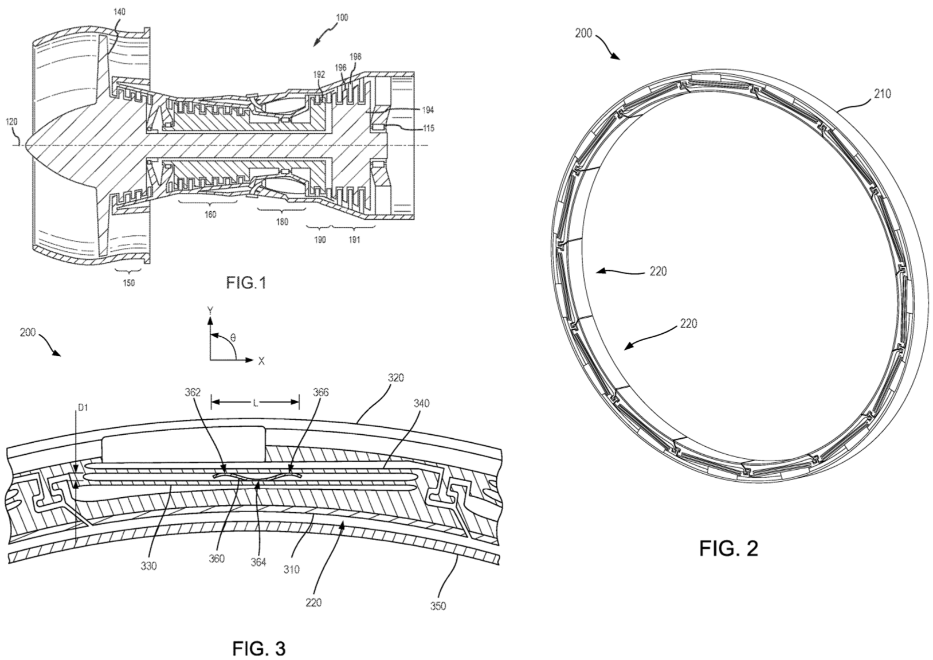


Figure 5: Patent Images for Non-contacting Dynamic Seal

2.3 Codes & Standards

2.3.1 Standard Practice for Outdoor Weathering of Construction Seals and Sealants (ASTM C1589/C1589M-18)

This standard will help implement ways into being more aware of the different weather conditions and how to work around them. This standard will help implement a weatherproof seal for the dynamic air capture machine. This is because if the air captures are placed in different locations on earth, then we need to make sure those conditions are accounted for in this modeling.

2.3.2 Standard Practice for Field Leak Testing of Polyethylene (PE) Pressure Piping Systems Using Gaseous Testing Media Under Pressure (Pneumatic Leak Testing) (ASTM F2786-16(2021))

This standard gives us the necessary methods we need to test the effectiveness of our seal. It provides the needed apparatus and safety precautions to test our seals. Ultimately this will give us the values we need to examine whether our seal meets the requirements of the company to accomplish our task.

2.4 User Needs

The customer needs were attained through a presentation by the customer and then a question and answer session. In the presentation, the customer introduced a 3D CAD model of the AirCapture carbon capture system and explained the design requirements (user needs) for the dynamic seal. Following that, the customer opened the floor to the engineers to ask questions. Section 2.4.1 below summarizes the primary questions and answers from the interview. Section 2.4.2 summarizes the interpreted customer needs that will be carried forward as design goals.

2.4.1 Customer Interview

Interviewee: Felix Winkler, Andrew Waldherr
Location: Google Meet, Online
Date: September 9^{th}, 2022
Setting: The interview was conducted via an online meeting where the design engineers at AirCapture presented and explained a 3D CAD model of the entire AirCapture system. After a thorough explanation, questions were asked on specific design challenges and requirements. The entire interview took ∼60 min.

Interview Notes:
How well does the seal need to work while the machine is rotating?

- It does not need to be sealed at the time of rotation, however, whenever it is not sealed, it becomes less efficient which matters.

How much human interaction can/are involved in rotation?

- None should be involved, the mechanism rotates every 90 seconds on an automatic cycle.

How much pressure should the seal be able to withstand?

- 250 Pa should be sufficient.

Will this seal be used in multiple orientations or just one?

- It will be used in all 360 degrees.

Do we have a size limit for the seal?

- Dimensions will be provided with the volume available.

Are there environmental considerations?

- The carbon capture systems will be outside in generally warmer climates, so salt spray and humidity should be considered.

What are the temperature restrictions?

- The seal should be generally low-cost to balance reliability and functionality.

If we were to use a pneumatic actuated system, what complications would arise?

- There is already compressed air used in the carbon capture device, so it is available but not preferred.

Are there any other concerns we should take into account?

- In general give preference to passive seals, however, a clever active seal could work as well. Also, the design does not need to be completely seal, just the better the seal, the more efficient the machine is.

2.4.2 Interpreted User Needs

Below is a chart highlighting the customer needs and preferences for the dynamic seal in the carbon capture machine.

Table 1: Interpreted Customer Needs

Need Number	Need	Importance
1	The seal completely stops any airflow from crossing the joint	3
2	The seal works while the mechanism is rotating	2
3	The seal is capable of withstanding 500 Pa of pressure	5
4	The seal is passive and requires no additional moving parts	4
5	The seal is capable of operating in warm coastal climates	5
6	The seal is capable of operating in temperatures between -10 and 30 degrees Celsius	2
7	The seal is simple and inexpensive to manufacture and install on carbon capture systems	4

After evaluating the customer needs, we recognized that the most important needs are to have the seal be capable of withstanding 250 Pa of pressure and operate in warm coastal climates. Whereas the less necessary items include being able to operate in more diverse climates and having no air escape during rotation.

2.5 Design Metrics

Below is a chart of target specifications for the dynamic seal. Target specifications show how each metric relates to a customer need and provide ideal/acceptable ranges for each metric.

Table 2: Target Specifications

Metric Number	Associated Needs	Metric	Units	Acceptable	Ideal
1	3	Total Pressure Delta	Pa	500	> 500
2	6	Total Temperature Delta	°C	$10 < T < 30$	$-10 < T < 30$
3	1	Max Airflow Past Seal	l/s	50	0
4	2	Sealing Mechanism Time Frame	sec	< 90	< 10
5	5	Lifespan	Year	10	> 10
6	2, 3	Violent Hazard of Failure, as specified in ASTM Standard ASTM F2786-16(2021)	Binary	Pass	Pass
7	5	Evaluation of effects of weathering should reflect intended use, as specified in ASTM Standard C1589	Binary	Pass	Pass

3 Concept Generation

3.1 Mockup Prototype

We designed a dynamic seal visualization and test prototype as seen in the pictures below. It is a two walled cylinder which can house the seal we design. This will allow us to model various types of seals for us to test their compatibility with the scaled model the seal should fit in. This housing is also removable, allowing for easy access to the inside area where the seal will be placed. Once we design the seal we desire, we can super glue the base to the walls, minimizing the air escaping when testing the pressure loss as we rotate our seal. Overall this housing prototype will guide us to making a suitable dynamic seal.

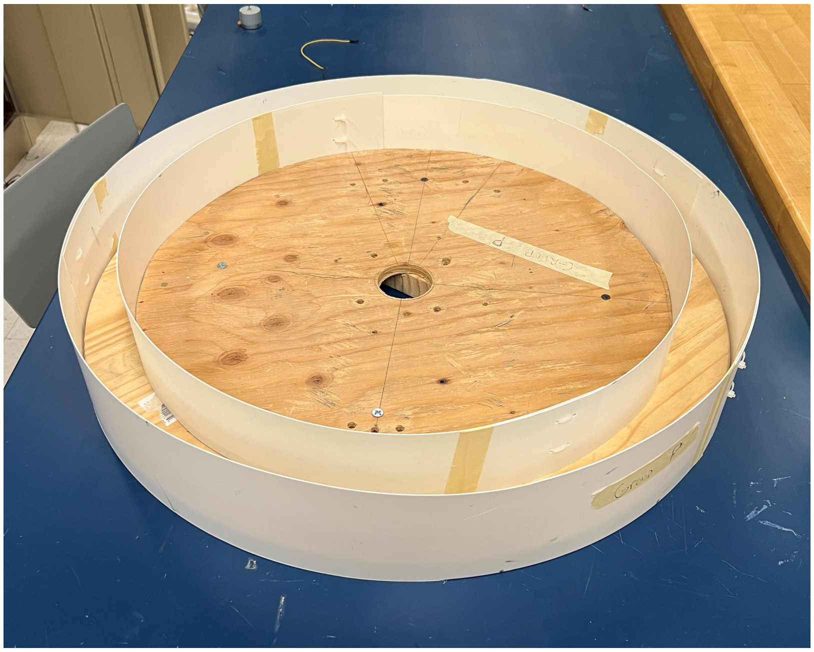


Figure 6: Dynamic seal visualization and test prototype: Fully Assembled

Figure 7: Dynamic seal visualization and test prototype: Base Only

Figure 8: Dynamic seal visualization and test prototype: With Walls Removed

3.2 Functional Decomposition

This function trees starts out with the overall function of a ”rotatable dynamic air-tight seal”. Then subfunctions were added based on certain design constraints and customer requests. The seal needs to function in coastal environments and that seal must be in effect when product is in operation. Visuals for each subfunction can be seen on the right with an evolution of a potential final product.

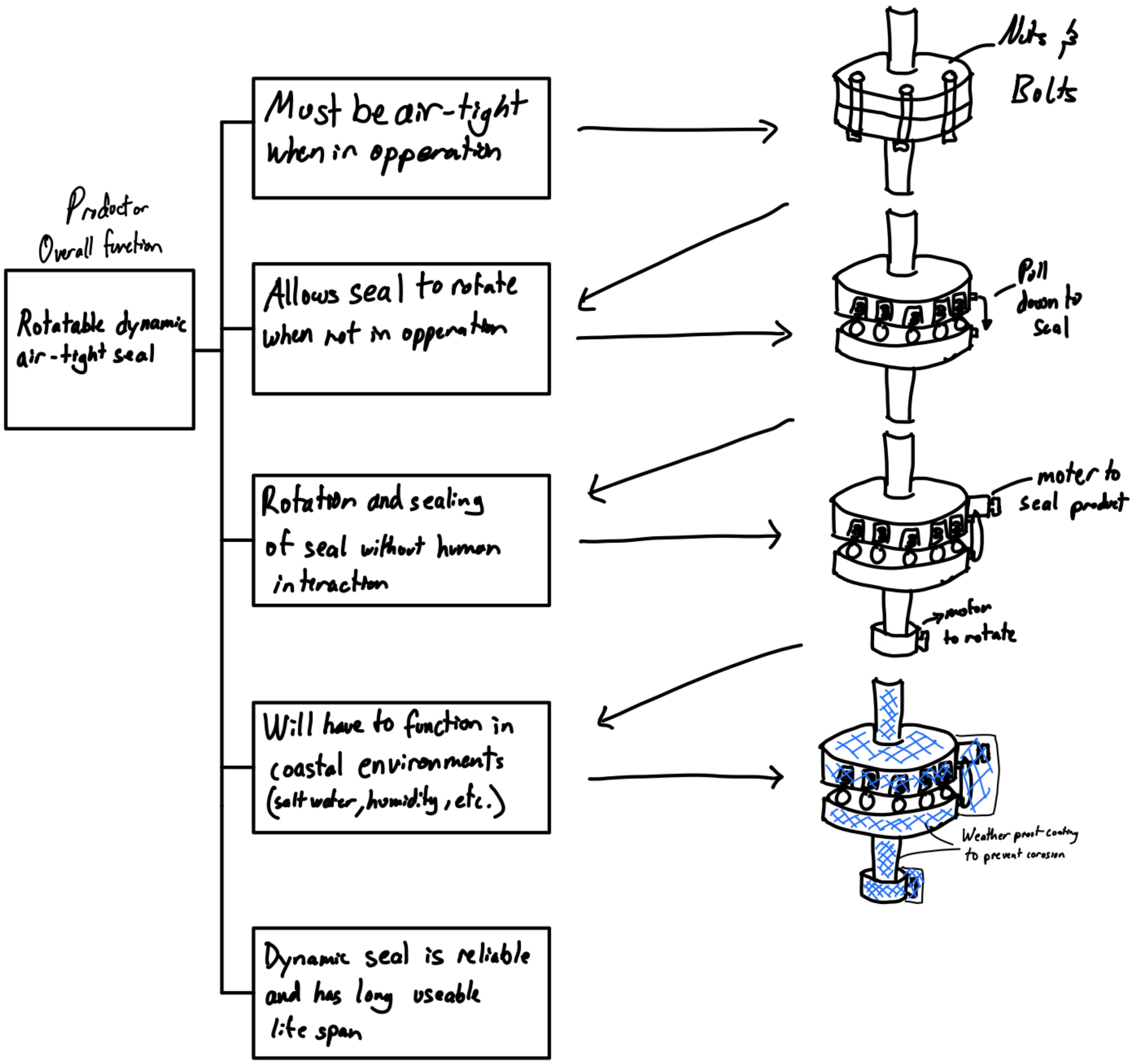


Figure 9: Function tree for Dynamic Seal, hand-drawn and scanned

3.3 Morphological Chart

This morphological chart contains five of the subfunctions followed by four potential solutions for each subfunction. The goal was to make each solution somewhat plausible to complete. Finally, concept were designed by choosing a solution for each subfunction.

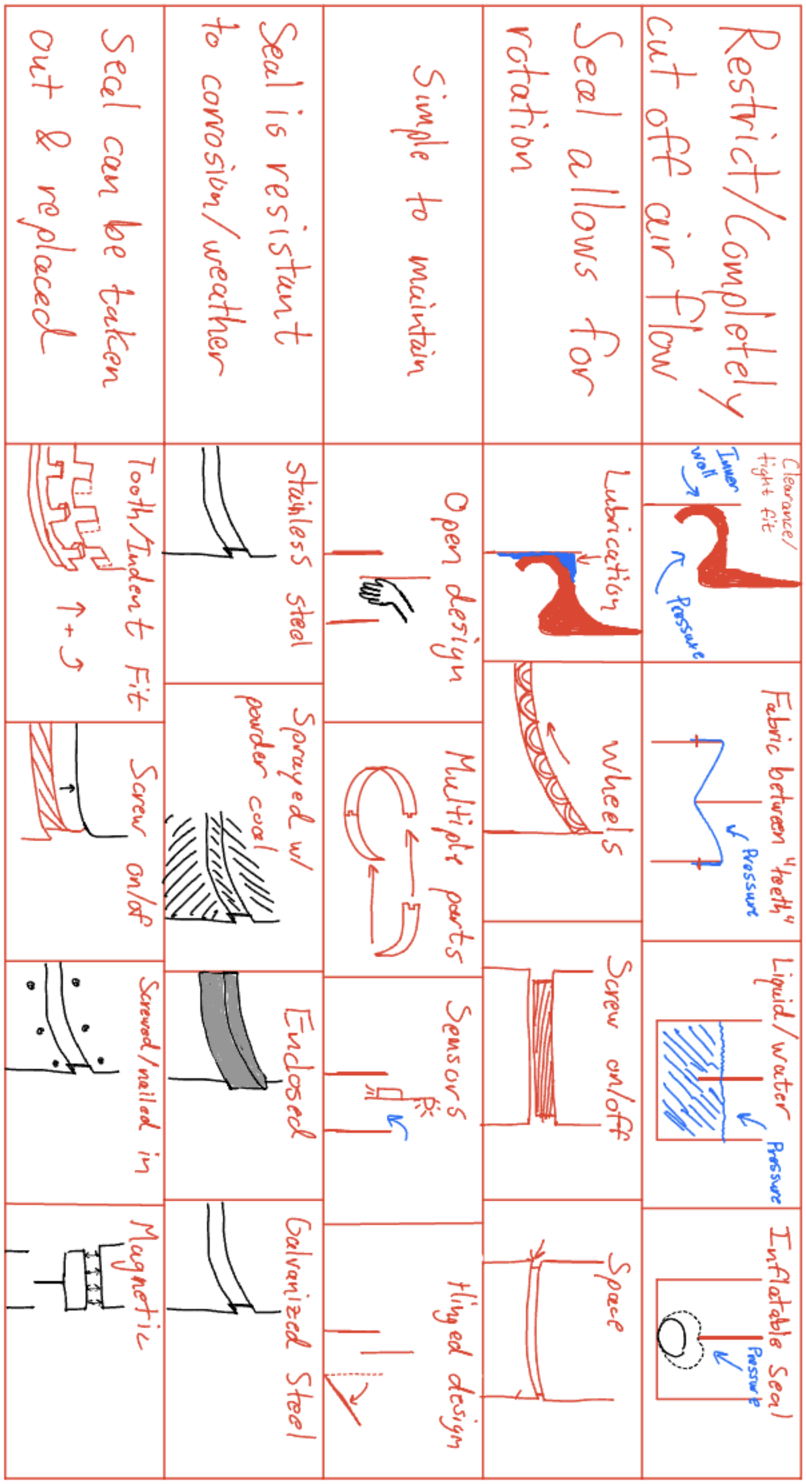


Figure 10: Morphological Chart for Dynamic Seal for Carbon Capture Machine

3.4 Alternative Design Concepts

3.4.1 Concept #1: Quarter Rubber Dynamic Seal

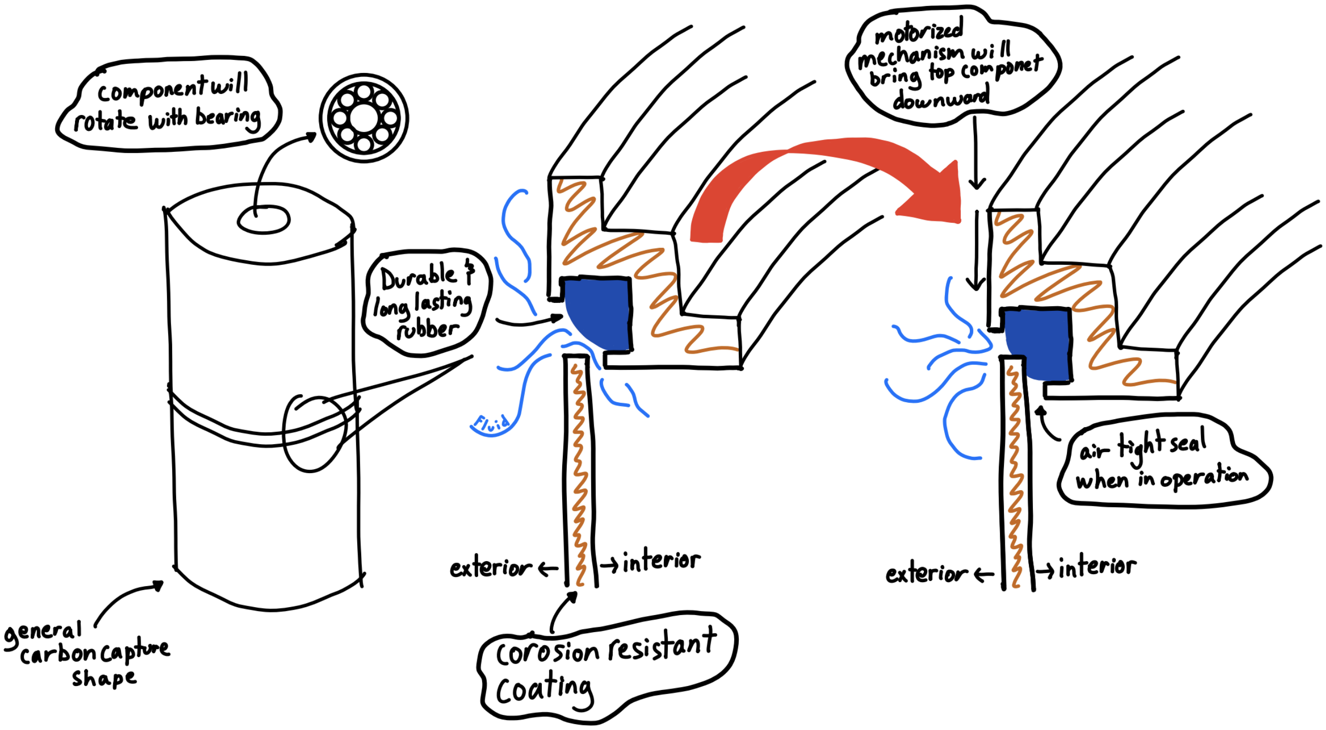


Figure 11: Sketches of Rubber Dynamic Seal concept

Description: This design uses a corrosion resistant coating and a bearing to rotate top component. The top component will be able to move down with a motor until it impacts the bottom component. As force is exerted on to the bottom component the quarter rubber will deform and create a seal. As the motor draws the top component upwards, the product will unseal.

3.4.2 Concept #2: Inflatinatior

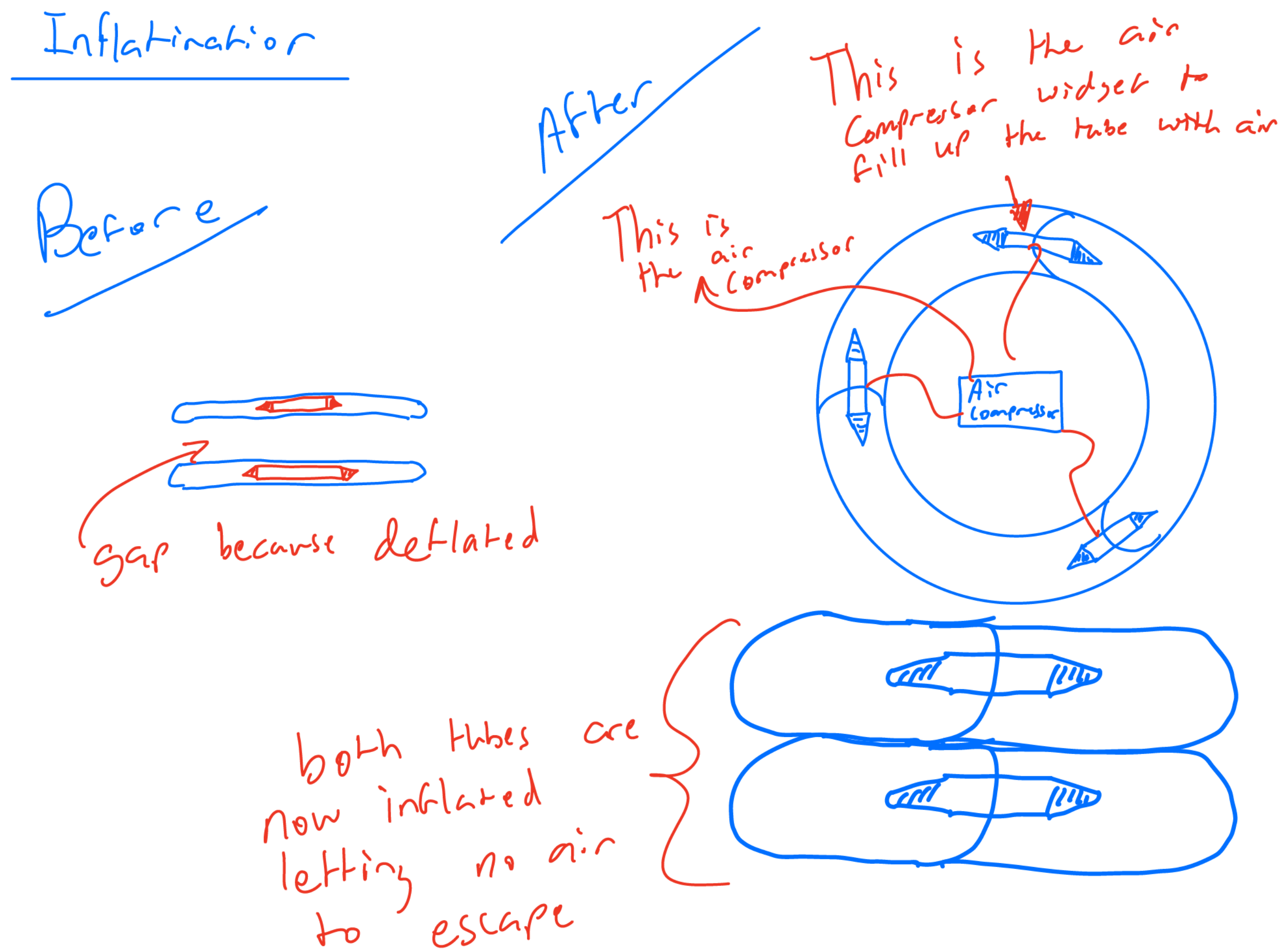


Figure 12: Sketches of Robotic Arm concept

Description: Above is the Inflatinatior. This design will house 2 inflatable rubber rings with air compressors inside it. To create the seal the rubber rings will inflate and become squished together, not allowing for air to escape. Once the air capture machine needs to rotate the rubber rings will deflate allowing for a slight gap between the rings. This gap will allow for the seal to be rotated as needed by the customer.

3.4.3 Concept #3: Plate-Press Seal

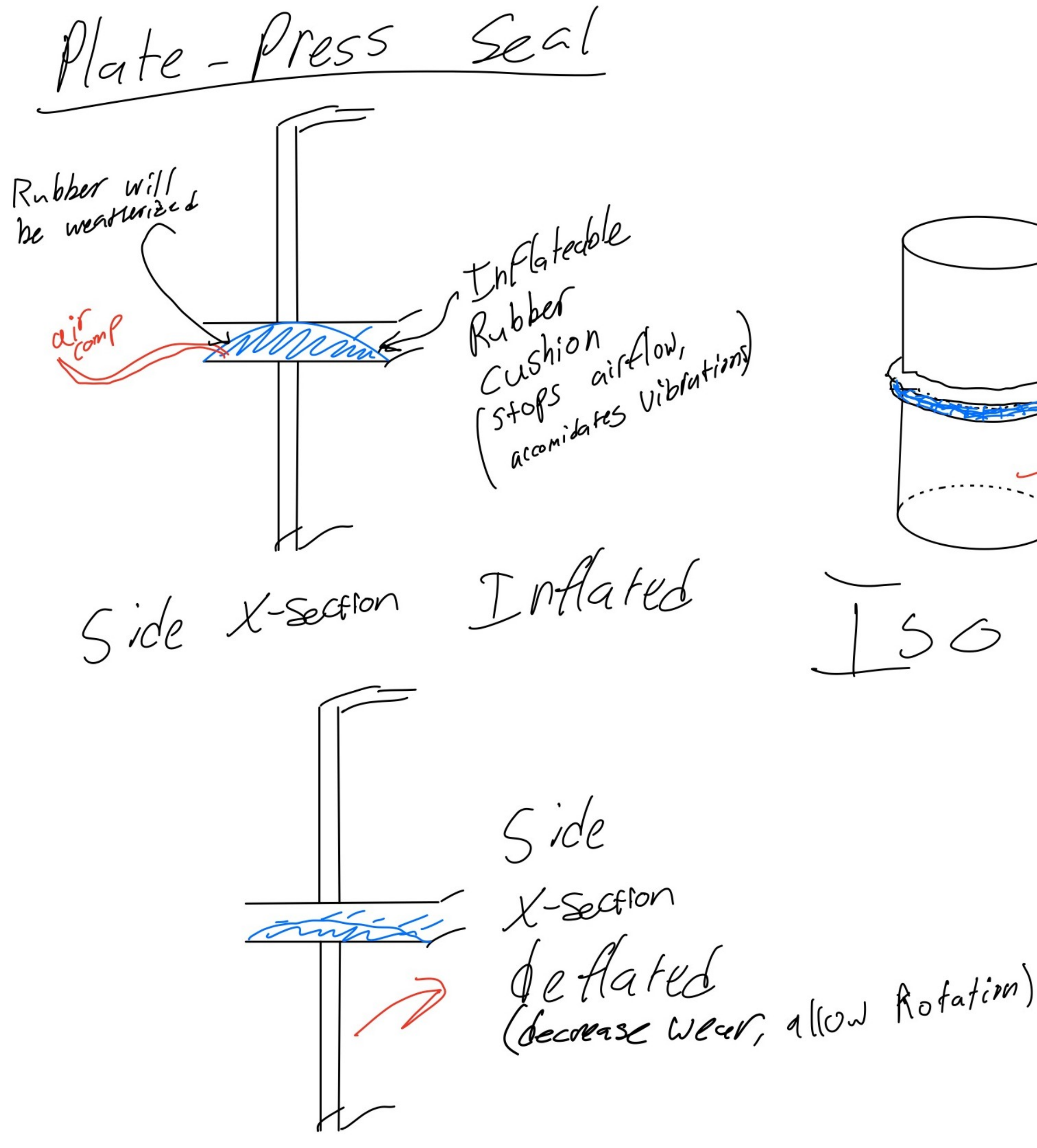


Figure 13: Sketches of Plate-Press Seal

Description: The Plate-Press Seal would take advantage of compressed air to inflate a semi-circle of weatherized rubber. This rubber tube would create a seal when inflated, allowing little to no air contamination. When the two halves of the machine needed to be rotated, the rubber tube would be depressurized slightly to make wear unlikely. Finally, when the rotation was done, the tube would reinflate and the seal would be complete.

3.4.4 Concept #4: Dynamic Tension Seal

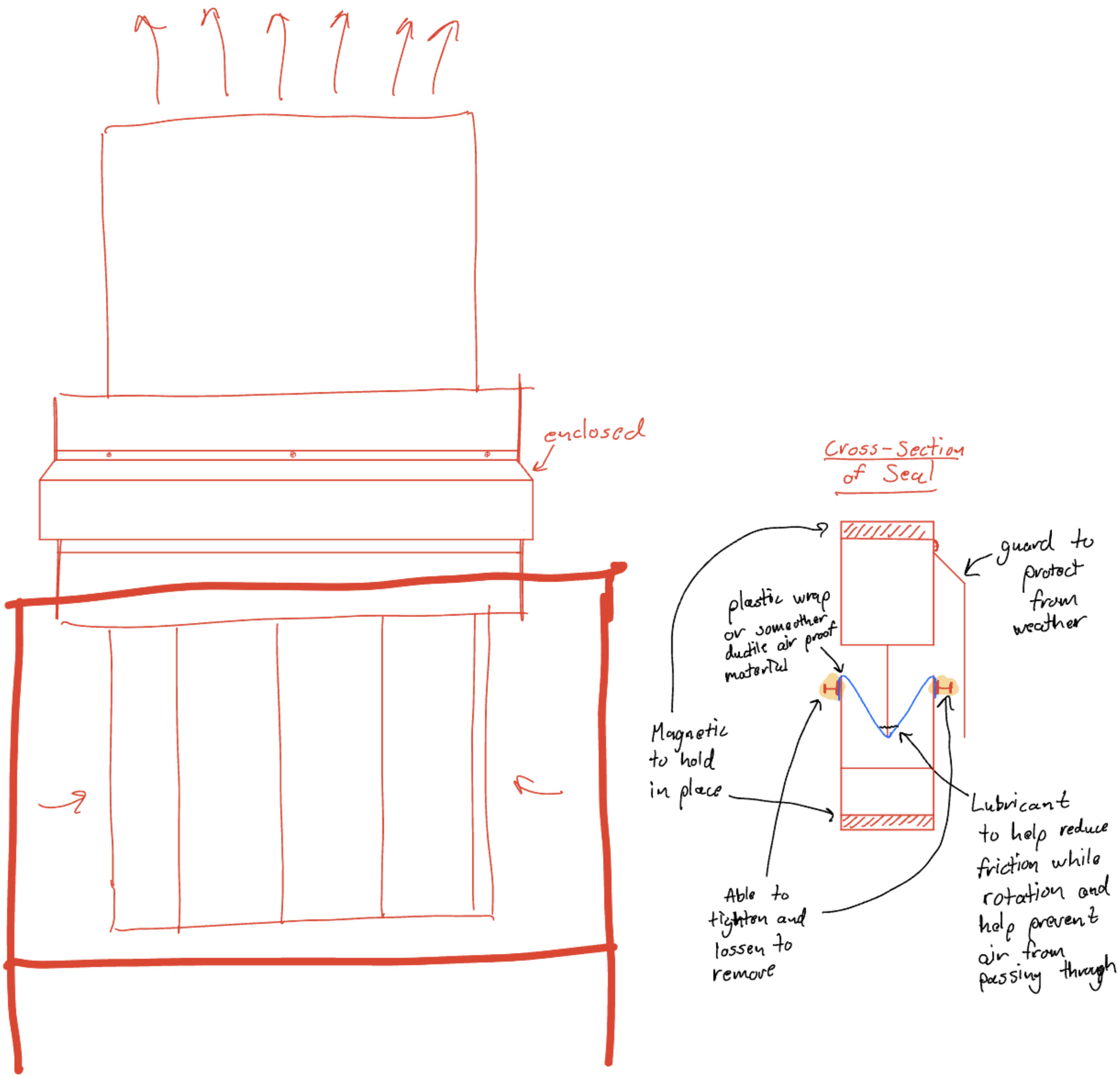


Figure 14: Sketches of Tension Seal concept

Description: Above is the Dynamic Tension Seal. This design involves a tooth and channel design that allows for the top and bottom of the carbon capture machine to interact with each other. Connected to the bottom part of the seal is some sort of elastic material that will create a seal when the tooth from the top meshes with the channel in the bottom. Some form of lubrication will be added to the material to lessen the wear from friction while rotating and help with the seal. The seal will also be enclosed to protect it from rain and elements. The pieces will be attached to the machine via magnets.

4 Concept Selection

4.1 Selection Criteria

Below, in Fig. 15, the table used to weigh the concept selection criteria is shown. This is an Excel template that allows the user to compare different characteristics of a product to each other. The table uses direct comparison between each criteria to create an unbiased overall weight percent to be used in the concept evaluation.

	Long Life	Seal is able to rotate	Withstand 500 Pa of pressure	Seal cost	Operates in diverse climates		Row Total	Weight Value	Weight (%)
Long life	1.00	0.14	3.00	1.00	5.00		10.14	0.17	16.79
Seal is able to rotate	7.00	1.00	7.00	7.00	9.00		31.00	0.51	51.31
Withstand 500 Pa of pressure	0.33	0.14	1.00	0.20	1.00		2.68	0.04	4.43
Seal cost	1.00	0.14	5.00	1.00	7.00		14.14	0.23	23.41
Operates in diverse climates	0.20	0.11	1.00	0.14	1.00		2.45	0.04	4.06
						Column Total:	**60.42**	**1.00**	**100.00**

Figure 15: Analytic Hierarchy Process (AHP) to determine scoring matrix weights

4.2 Concept Evaluation

The concept evaluation presented below in Fig. 16is based on the weight percent of the consumer needs presented above. This evaluation ranks all the seals from best to worst based on its ability to fulfill the users needs. We found the Dynamic Tension seal to be the best fit for the consumer.

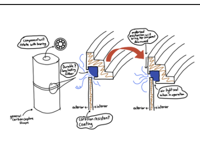
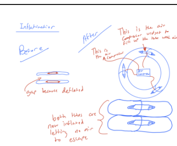
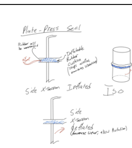
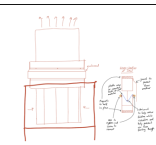
Alternative Design Concepts		**Quarter Rubber**		**Inflatinatior**		**Plate-Press**		**Dynamic Tension**	
									
Selection Criterion	**Weight (%)**	**Rating**	**Weighted**	**Rating**	**Weighted**	**Rating**	**Weighted**	**Rating**	**Weighted**
Long life	16.79	5	0.84	3	0.50	4	0.67	3	0.50
Seal is able to rotate	51.31	5	2.57	5	2.57	5	2.57	5	2.57
Withstand 500 Pa of pressure	4.43	4	0.18	5	0.22	5	0.22	5	0.22
Seal cost	23.41	1	0.23	2	0.47	3	0.70	4	0.94
Operates in diverse climates	4.06	4	0.16	4	0.16	4	0.16	4	0.16
	Total score	**3.979**		**3.921**		**4.323**		**4.390**	
	Rank	**3**		**4**		**2**		**1**	

Figure 16: Weighted Scoring Matrix (WSM) for choosing between alternative concepts

4.3 Evaluation Results

The top-ranked concept is the dynamic tension seal. The dynamic tension seal was given a score of 3 for the long-life criteria because the friction will wear at the film leading to a shorter lifetime, lubrication can be added to increase lifetime. It is critical that the bottom half of the machine can rotate, the machine will not be able to function if the bottom half is impeded in its rotation. This is why the dynamic tension seal was given a score of 5 because it does not restrict the rotation of the machine. The seal was given a score of 5 for the ability to withstand 500 Pa of pressure because 500 Pa is a very small pressure it will not take very much force between the film and the tooth of the seal that goes into the channel. This seal is relatively low cost because it is using the design already in use by the client but adding a flexible film in place of the water seal which is why it was given a score of 4. The seal was given a score of 4 in its ability to operate in diverse climates because the film shouldn't be seriously affected by the climate it is in, but experiments would need to be performed to check how the film is effected by extreme cold and heat.

4.4 Engineering Models/Relationships

4.4.1 Factor of Safety

The factor of safety is a value that tells us how much larger a property is than its required value. This will allow us to see if our machine is stronger than its intended use. A reasonable value will prove to the consumer its actual longevity and real-life applicability. We can find the pressure that the seal could withstand from its material properties and other assumptions, along with the applied load. With this, we can identify its factor of safety and determine its efficiency. The FOS can also be set as a value, and from this, we can calculate a measurable value that our seal must be able to achieve to pass. This will allow us to compare the other seal designs we have discussed to implement in the carbon capture machine for the best longevity.

$$FOS = \frac{StructuralCapability}{AppliedLoad} \tag{1}$$

4.4.2 Angular Velocity

This model will be used to find the angular accelerations required at each point in our design in order to accurately emulate the function of the client's machine. Using these numbers, a stepper motor will be able to be programmed in order to produce the desired motion. This will allow us to test our seal efficiently in a real-life situation, similar to the carbon capture machine.

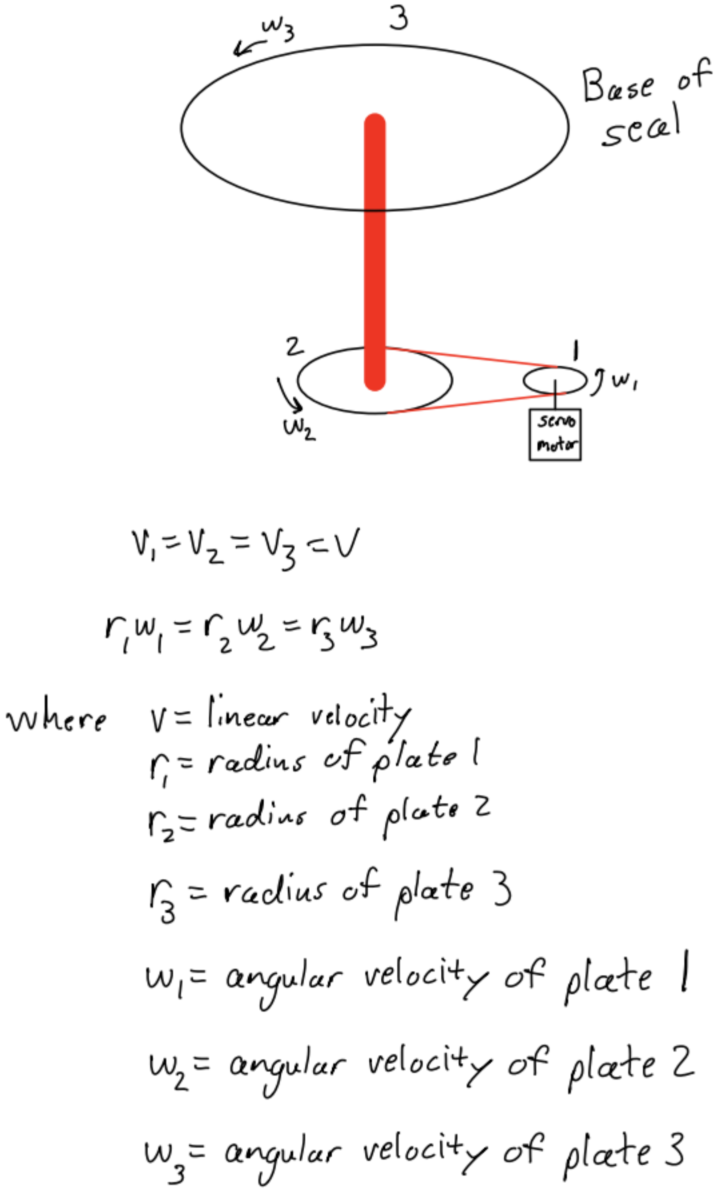


Figure 17: Engineering model for Angular Velocity

4.4.3 Shear Stress

The final engineering model we are introducing is a fluid dynamic model of shear stress in small channel Couette flow. This model will help us understand the applied shear stresses on the seal by the lubricating fluid. With this model, we can evaluate different lubricants depending on their viscosity, and the impact it will have on the seal's life. The original equation is

$$\tau_{wall} = \mu \left(\frac{du}{dy} \right) \tag{2}$$

where τ_{wall} is the wall shear stress, μ is the dynamic viscosity and u and y are the upper plate velocity and height respectively. This equation can be simplified to

$$\tau_{wall} = \mu \left(\frac{u}{y} \right) \tag{3}$$

as the gap is very small.

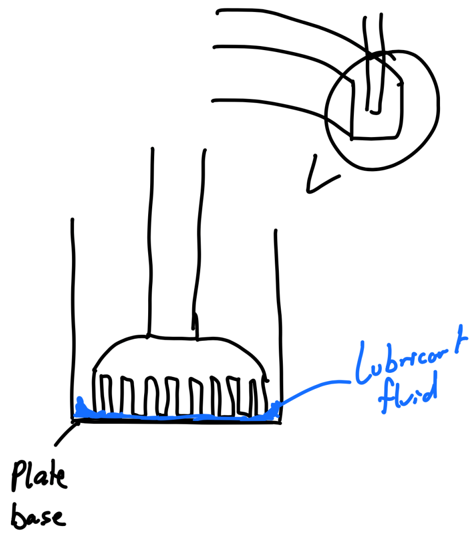


Figure 18: Engineering model for Shear Stress

5 Concept Embodiment

5.1 Initial Embodiment

Below are the CAD drawings of our initial prototype. The first drawing is a three-view with an isometric view and section views. The second is a larger isometric view with sections, and the final drawing is an exploded view with a bill of materials.

Our **prototype performance goals** are:

1. After adding water to one side of the seal (to emulate the pressure differential while in use), the other side of the seal is still dry when checked 12 hours later.
2. After adding water to one side of the seal and leaving the machine to rotate continuously, the water level has not completely "leveled out" after 24 hours.
3. After leaving the machine to rotate continuously for one week, the test from Goal 1 is repeated.

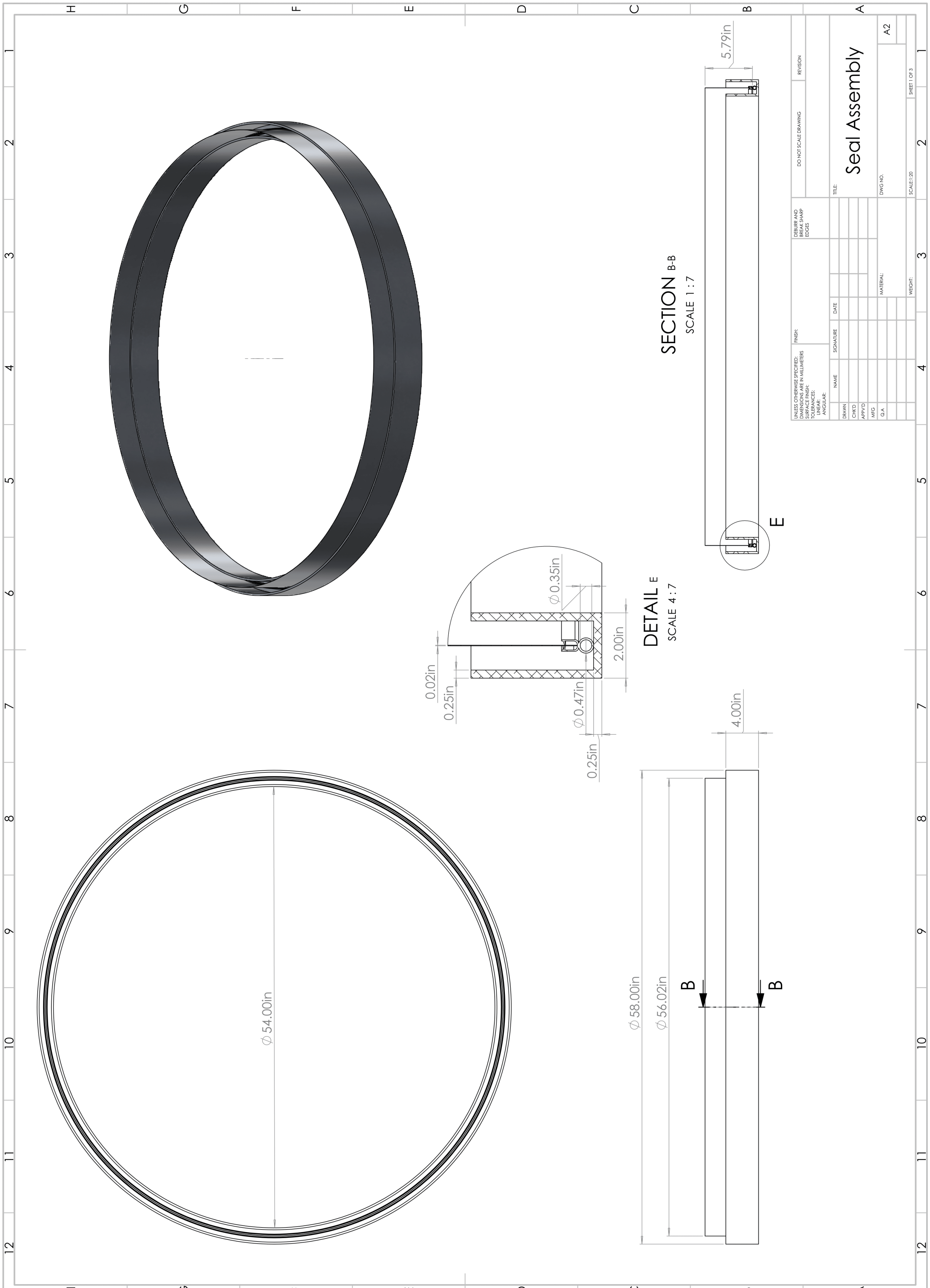


Figure 19: Assembled projected views with overall dimensions

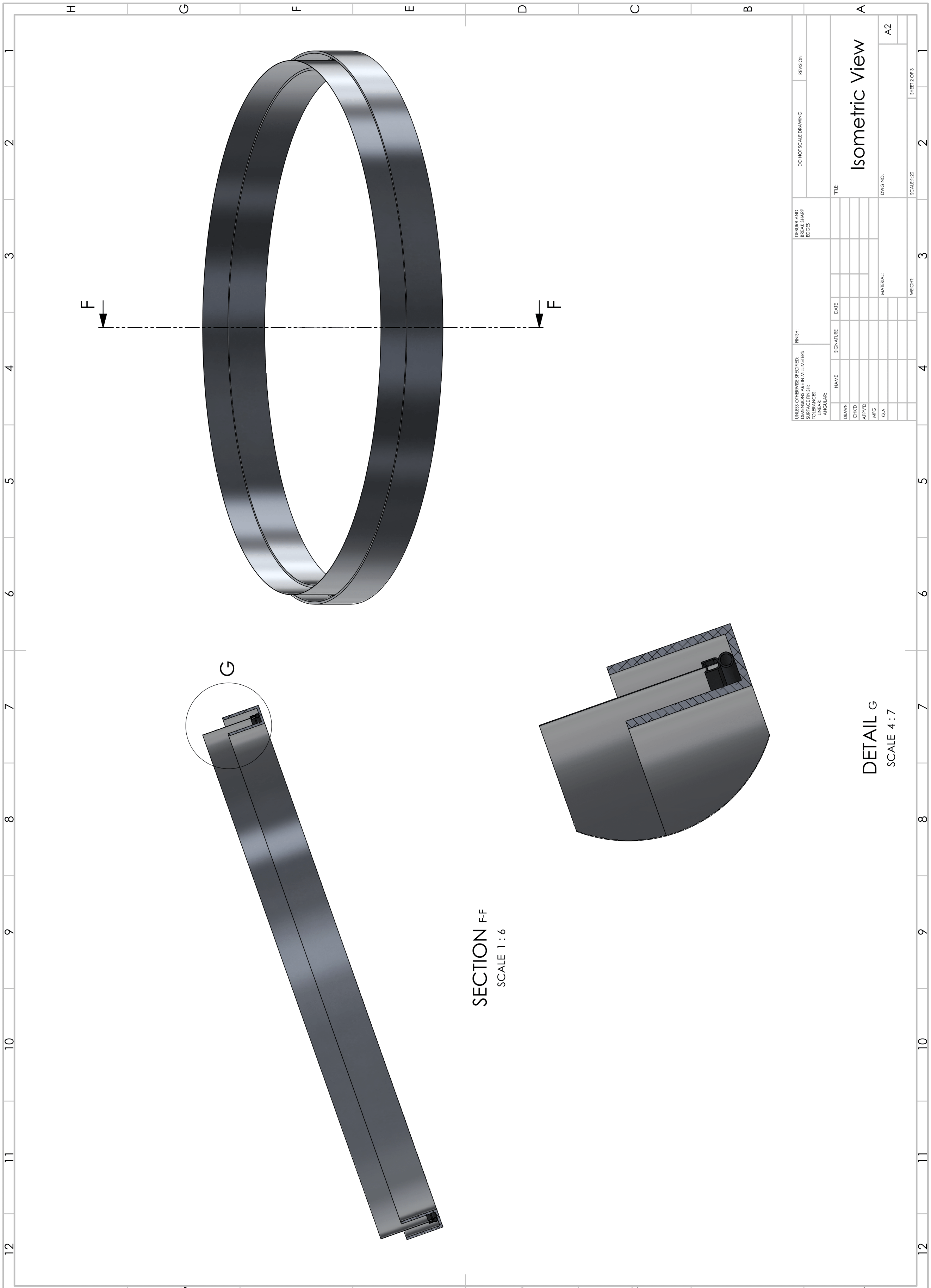


Figure 20: Assembled isometric view with a detailed view of section cut

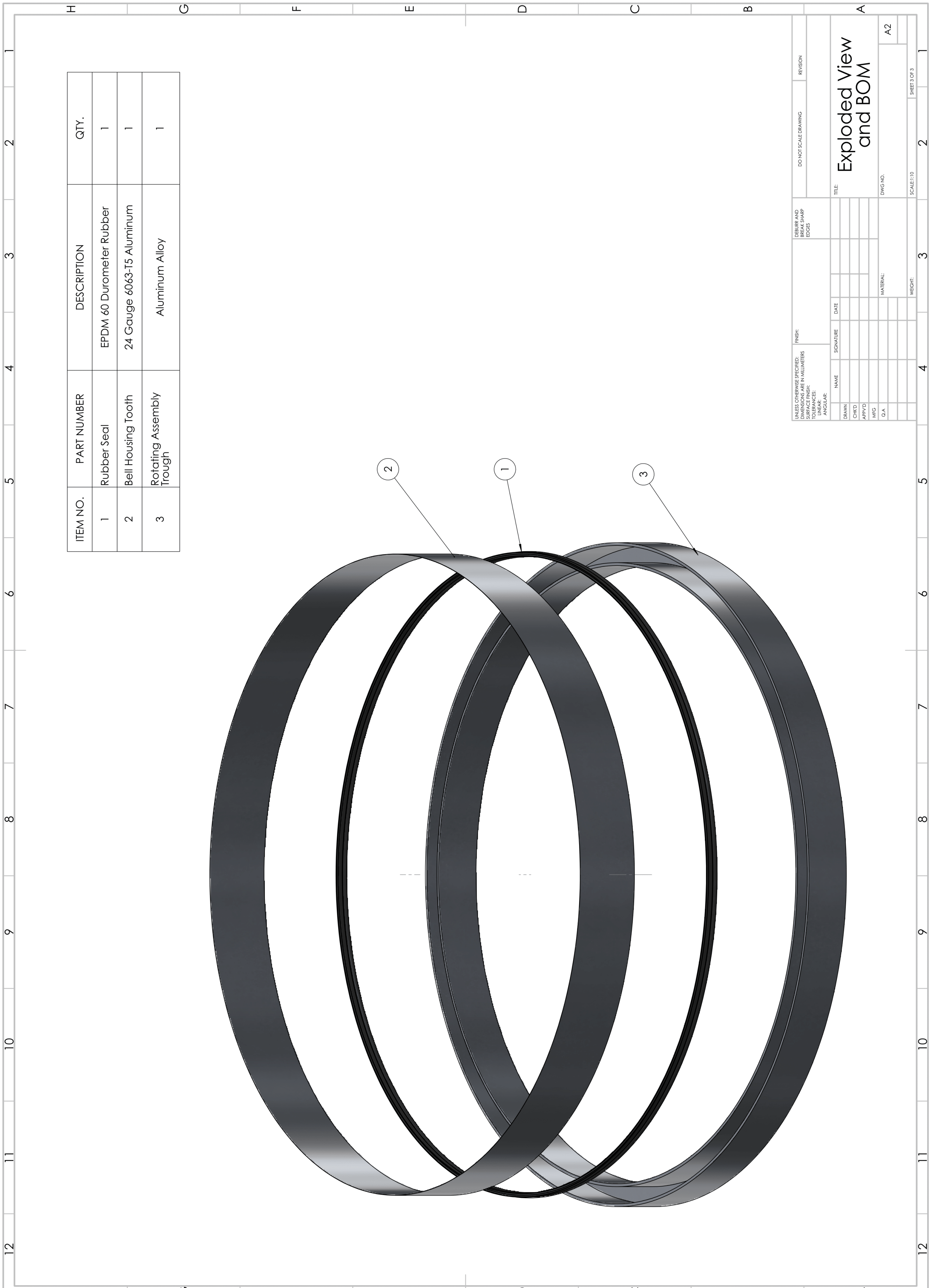


Figure 21: Exploded view with a bill of materials (BOM)

5.2 Proofs-of-Concept

Our group did not perform proof of concept testing. Instead, we built a test structure to visualize how our seal would work. While building the test structure, we had to account for the width and depth of the trough on the base of the structure so that the tooth could fit into the space easily. In addition, we had trouble automizing the rotation of the base structure and we decided to use a wheel on a motor to apply friction to the base structure causing it to rotate. These are a couple of the problems we had to account for while building our test structure.

5.3 Design Changes

Our initial concept design for the dynamic seal compared to our initial prototype had many similar components, however, some components like the electromagnet, plastic wrap, and guard were not implemented. These components were not implemented because they were either going to be implemented in our much more advanced prototype, like the electromagnet releasing the seal, or did not have a great effect. Our prototype seal was made with a rubber weather strip that would be attached to a metal tooth. This weatherstrip was then inserted into the middle of the trough to seal the inside of the machine from the outside. The next main portion of our concept design was the oil lubricant for easy seal rotation, in our prototype we replaced the oil with grease because it was difficult and very expensive to purchase high-density oils. Finally, the trough in our prototype was squared out instead of a “V” shape. Our intention is to create the next prototype with a “V” shaped tough because it will allow grease or oil to funnel into the middle and not remain displaced when the seal is rotated. Overall, we kept the concept design very similar to our prototype and made necessary practical adjustments.

6 Design Refinement

6.1 Model-Based Design Decisions

In section 4.4, engineering models/relationships were introduced. In this section, we will be explaining how we applied certain engineering models to specific parts of our prototype.

6.1.1 Factor of Safety

The factor of safety was defined and explained in section 4.4.1. We considered a maximum seal pressure of 500 Pa. During our static water test, we used Bernoulli’s equation to calculate the amount of water needed to produce 500 Pa of pressure force on the seal, see section 6.1.2 for further explanation on Bernoulli. The requirement of 500 Pa is the most pressure differential that the seal will withstand. This is why we decided to go with a factor safety of 1 as a preliminary testing condition.

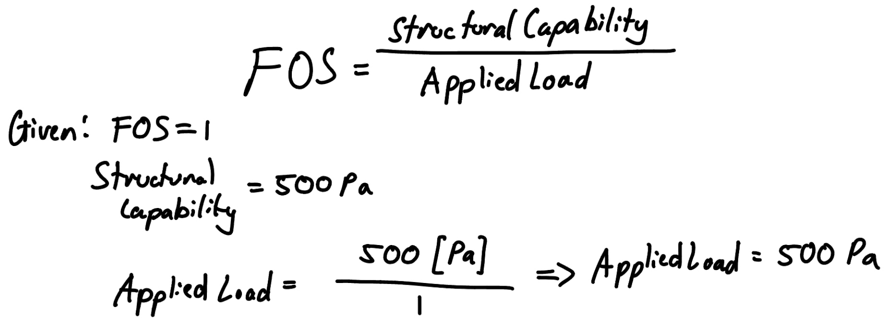


Figure 22: Applied Load calculation using a factor of safety

Using equation 1 and a factor of safety of 1 we are able to then calculate the structural capability. The applied load of the system is considered to be 500 Pa.

6.1.2 Bernoulli's Equation

To calculate the amount of water needed to create the desired pressure differential for testing, Bernoulli's equation was employed. Bernoulli's equation, shown in Eq. 4, relates pressure, fluid velocity, and potential energy of a fluid. It states that for inviscid flow along a streamline, the summation of velocity, pressure, and potential energy will be constant.

$$p_1 + \frac{1}{2}\rho V_1^2 + \rho g z_1 = const. \tag{4}$$

The Bernoulli equation was used to calculate the depth of water required to create the 500 Pa pressure differential needed for testing. The calculation can be seen below in Fig. 23.

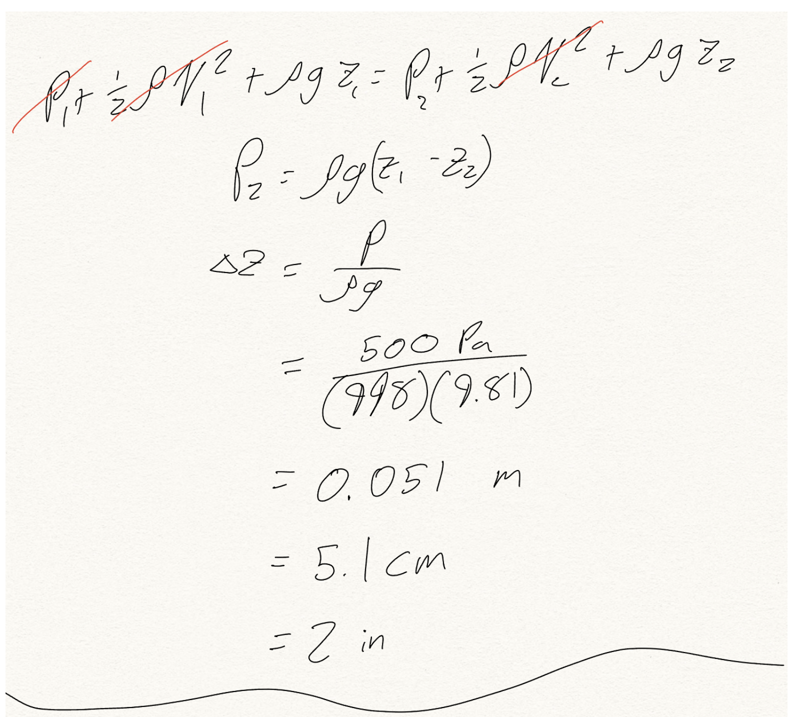


Figure 23: Water depth calculations using Bernoulli

To calculate the depth of water needed, the Bernoulli equation was considered across two points, one at the base of the seal and the other some height up in the trough. In the calculation, the velocity was assumed to be zero at both points and the z coordinate was set to zero at the base of the seal. The pressure at the surface was assumed to be zero as we worked this problem in gauge pressure. The equation was then solved for the height z of the water. The calculation showed that we should use roughly 2 inches of water.

6.1.3 Angular Velocity

To calculate the angular acceleration of the base so that the prototype would accurately represent AirCapture's machine the relation below (Eq.5) was used. The relation states that if two circular objects are rotating and share one point of contact, assuming no slip, the velocity will be equal.

$$r_1 w_1 = r_2 w_2 \tag{5}$$

The angular velocity equation was used to determine the angular velocity at the base rotated when the motor was running at its slowest speed. The calculations performed can be seen in figure 24.

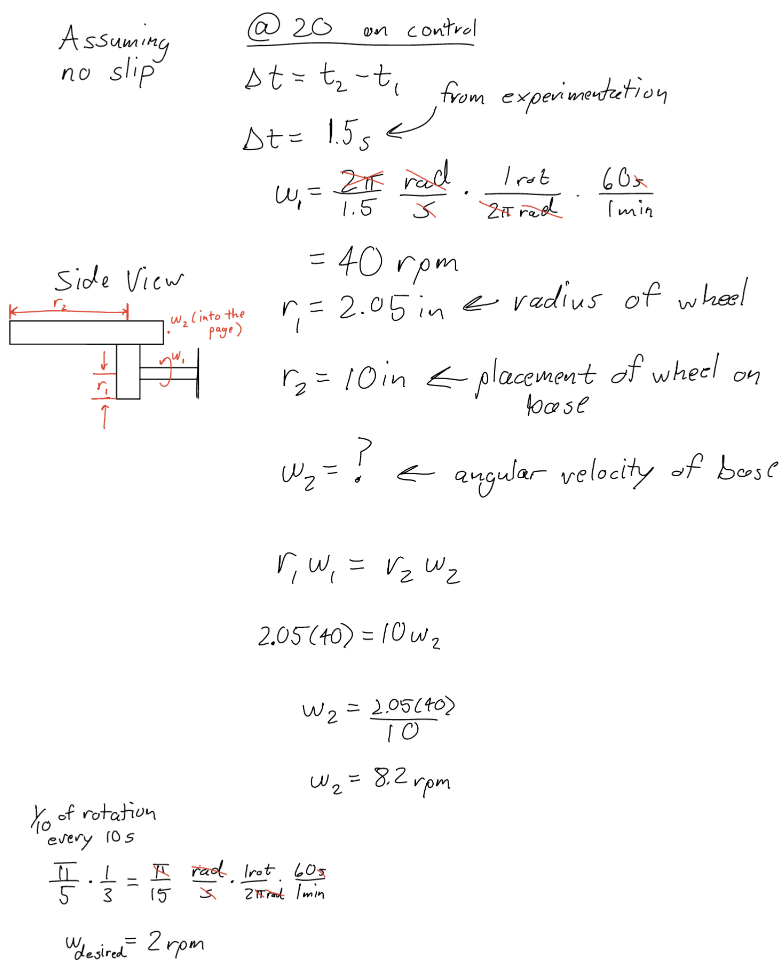


Figure 24: Engineering model for Angular Velocity

These equations were used to find the theoretical angular velocity of the base of the prototype when the motor was moving at its slowest speed. In the calculation, the angular velocity of the wheel was found by using a camera to record the wheel in motion and using the time stamps to find the time it took to make a full rotation. The radii of the wheel and where the wheel is located on the base were found by measuring the parts. Thus, there were three known to plug into Eq. 5 to solve for the angular velocity of the base. The minimum angular velocity was found to be greater than the desired angular velocity and there is no feasible way for us to gear it down so we did testing with the 8.2 RPMs found.

6.2 Design for Saftey

In this section, we will go over the design risk assessment.

6.2.1 Risk #1: Rubber Tears

Description: The rubber seal tears off jamming the machine, and causing internal damage.
Severity: Marginal
Probability: Unlikely
Mitigating Steps: Adding more grease during regular maintenance.

6.2.2 Risk #2: Rotating Wheel Slips

Description: The wheel is interfaced with a wooden piece connected to the motor. The wooden piece is eccentrically connected to the wheel which makes it easily separable during its constant rotation.
Severity: Marginal
Probability: Occasional
Mitigating Steps: Creating a concentric and more tight fitting connection between the wheel and the motor.

6.2.3 Risk #3: Motor Overheats

Description: The motor overheats, causing a fire.
Severity: Catastrophic
Probability: Unlikely
Mitigating Steps: The motor has a breaker that stops the motor before it overheats.

6.2.4 Risk #4: Rubber Seal Melts/Deforms

Description: The grease gets displaced causing the rubber to have lots of friction with the base, causing a fire. Since our design is made of wood that would burn the entire machine down.
Severity: Marginal
Probability: Unlikely
Mitigating Steps: Adding more grease during regular maintenance.

6.2.5 Risk #5: Catastrophic Structural Failure

Description: After constant rotations the wooden posts and base splinter, eventually causing the entire design to fall apart.
Severity: Catastrophic
Probability: Unlikely
Mitigating Steps: Replace the wood with a hard metal like steel.

		Probability that something will go wrong				
	Category	**Frequent** Likely to occur immediately or in a short period of time; expected to occur frequently	**Likely** Quite likely to occur in time	**Occasional** May occur in time	**Seldom** Not likely to occur but possible	**Unlikely** Unlikely to occur
Severity of risk	**Catastrophic**					Motor Overheats Catastrophic Structural Failure
	Critical					
	Marginal			Rotating Wheel Slips		The rubber tears Rubber Seal Melts/Deforms
	Negligible hazard presents a minimal threat to safety, health, and well-being of participants; trivial					

Figure 25: Risk Severity Heat Map

According to the Heat Map shown in Fig 25, most of the risks fall under the moderate prioritization category. The risks, in yellow, that fall under this category are the motor wheel slipping off, the motor overheating, and catastrophic structural failure. However, the motor wheel slipping off is considered a higher priority among those three risks due to it occurring more likely than the other risks. The next risks that take priority are the rubber seal tearing causing internal damage and the rubber melting causing a fire. These risks are low priority, in green, because they are very unlikely to occur.

6.3 Design for Manufacturing

6.3.1 Number of Components

The number of components of our seal design is 3; the tooth, the rubber seal and the trough, as seen in Fig. 21. There are no fasteners in our design as all joints are welded.

6.3.2 Theoretically Necessary Components (TNC)

All of the components of our design are needed for it to function, so the TNC is 3. Because of the simplicity of our design, eliminating components is rather impossible. Because no components can be removed, there are no design modifications to propose.

6.4 Design for Usability

In this section, we will propose ideas to modify our prototype to improve usability for people with certain impairments.

6.4.1 Vision Impairment

The usability of this device isn't influenced by human interaction. This carbon capture machine should be able to run for long periods of time, maintenance is predicted to happen quarterly (4 times a year). This means that there will be very minimal human interaction with the device. When the dynamic seal needs to be repaired, people in maintenance may have a hard time locating the rubber component of the seal. To combat this, the rubber component can be neon orange, so that it can be easily located.

6.4.2 Hearing Impairment

When the dynamic seal of the carbon capture machine is in operation and rotating the system can be somewhat hazardous to someone with hearing impairment. To combat this, when the dynamic seal is rotating, a loud beeping sound (similar to the sound when a car reverses) can be played to make sure one with a hearing impairment is aware of the carbon capture machine and can safely move around it.

6.4.3 Physical Impairment

The dynamic seal will be motorized and self-powered, meaning it requires essentially zero influence from human interaction for it to run, as it will all be automated. This means one with a physical impairment would have no effect on the usability of the machine. However, when the seal needs to be replaced, making sure that the dynamic seal can be easily accessed for maintenance will help prevent injuries. If it's hard to access one may have to use a tool in an awkward orientation that can cause possible injuries.

6.4.4 Control Impairment

To prevent people with control impairments from hurting themselves when coming near or interacting with the machine, a sign can be posted to make sure that only trained professionals (those in maintenance) can interact and get near the machine. In addition, some sort of protective guard (fencing) around the dynamic seal will help prevent people with control impairments to interact with the dynamic seal.

7 Final Prototype

7.1 Overview

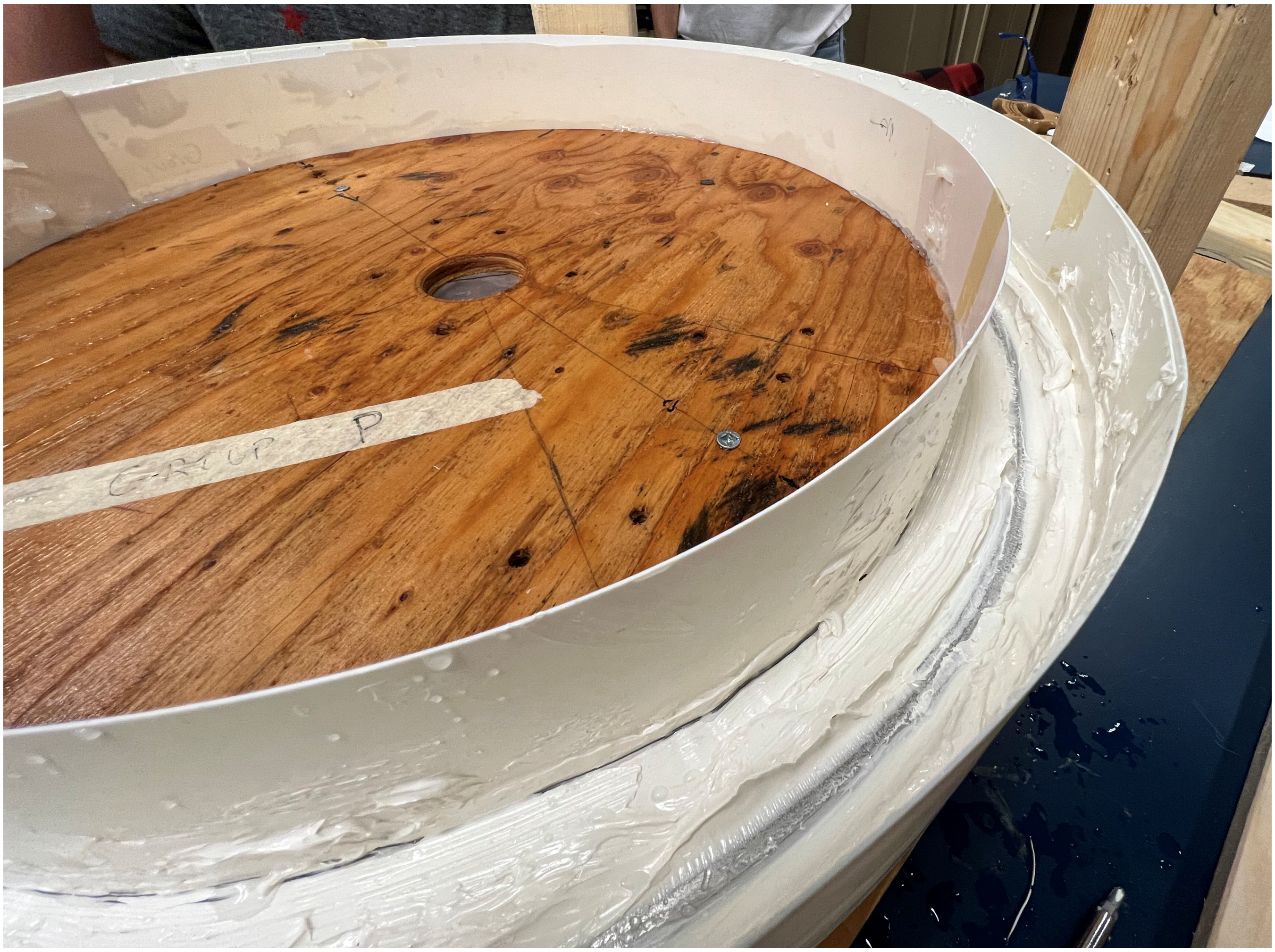


Figure 26: View inside the seal trough

Above is Figure 26, this figure shows the trough that the tooth from the top section of the seal rests in. Grease has been applied to the bottom section of the trough in order to reduce the amount of friction between the tooth and the base of the trough. This reduction in friction will assist movement and the lifespan of the seal.

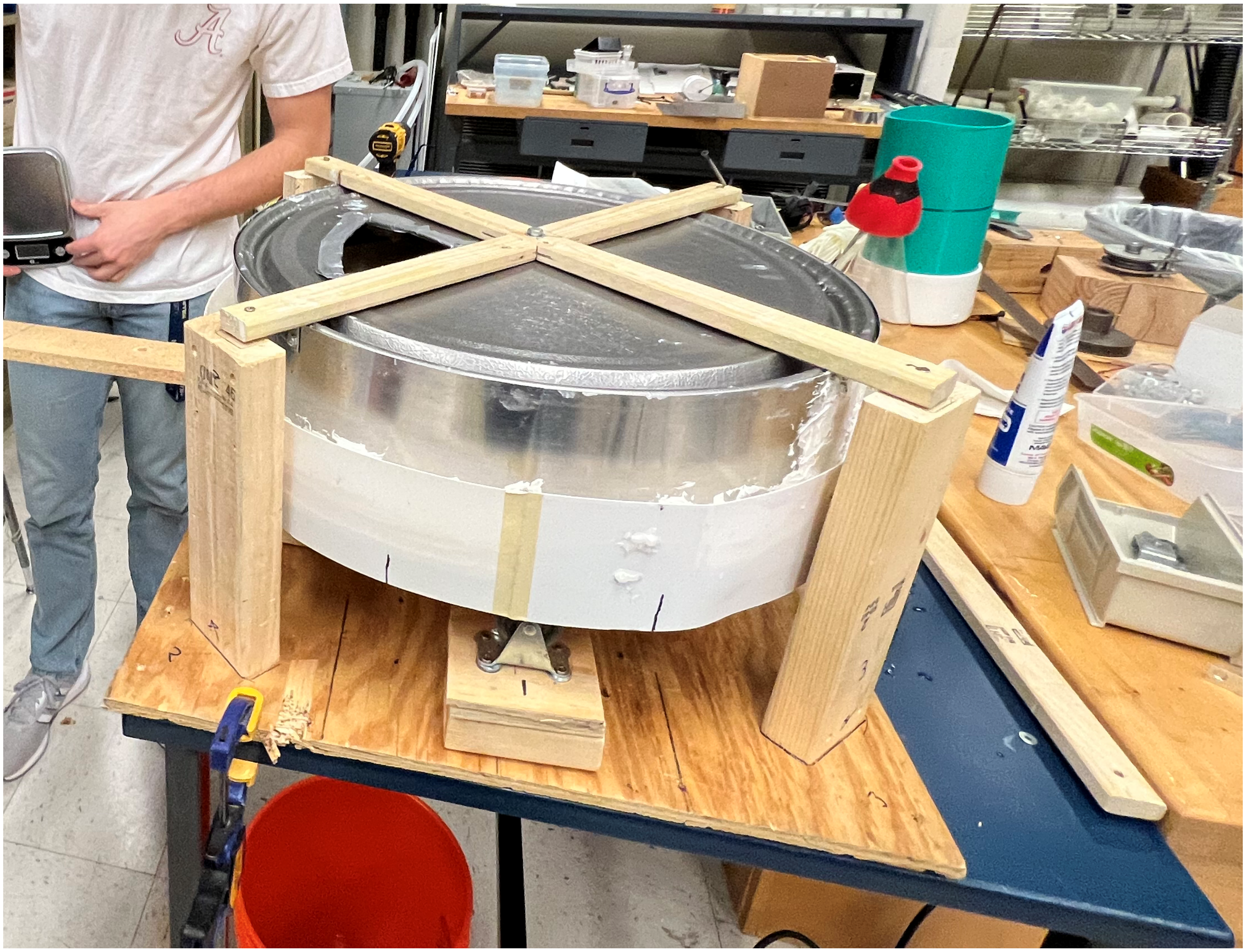


Figure 27: Complete final prototype

Figure 27 shows the final assembly of the dynamic seal. In this assembly, the bottom section of the seal rotates while the top section interfaces with the bottom by pressing a tooth fitted with weatherstripping into the base see Figure 26. This final design can utilize either a motor or hand power to rotate. The motor is attached to the opposite side of the rig and rotates the assembly via friction applied by a wheel to the underside of the base of the seal. Another wheel, which can be seen in Figure 27, was placed opposite the mounting position for the motor in order to add stability to the base. A circular bearing was connected to the underside of the base and connected to a stationary wooden structure on the underside of the base, this allows the base to rotate relatively easily. Finally, the top is held above the base as a support structure in order to simulate AirCapture's actual machine which has a rotating bottom and stationary top section.

7.2 Documentation

Below are hyperlinks to videos of the prototype undergoing 3 different tests.

1. Testing the torque it takes to rotate.
2. Testing whether the seal is able to withstand 500 Pa of pressure for 1 hour without moving
3. Testing whether the seal is able to withstand 500 Pa of pressure while hand rotated